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New Method for High Impedance Faults Detection Using Total Harmonic Distortion Properties and Time Variations of Current Waveform *

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(Abstract) High Impedance Faults (HIFs) detection has always been difficult, because their signs are not clear. This paper presents a new method for HIFs detection in distribution networks. The proposed method can easily discern the HIFs from other same phenomena in distribution networks such as capacitors switching, linear and nonlinear loads switching. This method has been used Total Harmonic Distortion (THD) properties and time variations of current waveform in four stages for HIFs detection. One advantage of proposed method compared to other methods is HIFs detection from random nonlinear loads switching.

Keywords: High Impedance Faults (HIFs); Total Harmonic Distortion (THD); Time Variations; Distribution Network.

1. Introduction

When an overhead conductor in distribution network touches a high impedance object such as branches of the tree or breaks down and touches ground, a HIF occurs. Basic property of HIFs is its difficult detection, because the current of these faults is not enough and generally cannot be detected by conventional over current devices. The main purpose for HIFs detection is different from Low Impedance Faults (LIFs), because the main purpose for LIFs detection is prevention of thermal and mechanical damages to network, however for HIFs due to low level fault currents do not cause much damage to network and their equipment, but the main purpose for HIFs detection is human lives' protection and prevention of fire hazards as a result of the arcing phenomenon [1].

Fault impedance in HIFs is total of the earth resistance, arc resistance and resistance between earth and conductor. Arc resistance is highly nonlinear due to changes in conductor contact with the earth during the arc extension, tubes silicon carbide production are due to the heating generated by the arc and other reasons [2]. Non-linearity of resistance of fault caused the current waveform distortion. This distortion creates harmonics in current waveforms which are good indicators for the HIFs detection. However phenomena such as linear and nonlinear loads switching and capacitors switching have the same properties as HIFs and during HIFs detecting these phenomenon should be separated from it.

Several algorithms and techniques have been researched and proposed for the detection of HIFs, including the magnitude of phase or natural fault current and voltage [3- 6], low order harmonics, sub-harmonics and low frequency spectrum [7-10], high frequency spectrum [11-15], fractal technique [16], kalman filtering technique [17], wavelet transform [18-21], expert system [22-26], fault current flicker [2], neural network [27-30], fuzzy logic [31-32], genetic algorithm[33-34].

In this paper the HIFs detection through the extraction of the THD Properties and time variations of current waveform in four stages is conducted. Theoretical analysis and MATLAB simulation results showed that the algorithm was able to detect HIF among other same phenomena in a sensitive and selective way.

2. Canonicals Used for Hifs Detection

In this paper, four canonicals have been evaluated for HIFs detection. These canonicals are based on THD, third harmonic and value of current waveform caused by HIF.

2.1. THD Extraction

The first canonical for HIFs detection is THD value of current waveform. For evaluating this canonical, in the first stage, current waveform harmonics are extracted by using Fast Fourier Transform (FFT). FFT is the same as Discrete Fourier Transform (DFT) and will produce the same result which directly obtained with the DFT. It is the only difference which

is much faster. Sine and cosine coefficients of FFT for signal *x(t)* are calculated with (1) and (2) relations.

$$S_i(P) = \sum_{n=1}^{N} x(n) sin(\qquad (1)$$

$$C_i(P) = \sum_{n=1}^{N} x(n)\cos\left(\frac{2\pi np}{N}\right) \qquad (2)$$

Where

x(n) is magnitude of nth sample.

N is data window length.

P is harmonic number.

*i*is number of data window.

n is nth sample of data window.

Harmonics amplitudes computed according to relation (3).

$$X_i(P) = \sqrt{\left(S_i(P)\right)^2 + \left(C_i(P)\right)^2} \qquad (3)$$

Then in the second stage, using the relations (4), (5) and harmonics extracted of the first stage, current THD is extracted.

$$THD = \frac{X_i(H)}{X_i(F)} \qquad (4)$$

$$X_i(H) = \sqrt{\sum_{P=2}^{n} (X_i(P))^2} \qquad (5)$$

Where

$X_i(P)$ is RMS value of Pth harmonic of ith data window.

$X_i(F)$ is RMS value of the fundamental components of the ith data window.

If the current THD is greater than the considered threshold, one of disturbances such as linear load switching, capacitor switching, nonlinear load switching or HIF can be occurred in network. Next canonicals are used for separation HIFs and other same phenomena.

2.2. Stability of THD

The second canonical for HIFs detection is stability of current THD. For evaluating this canonical, the current THD for *M* consecutive sample data windows is calculated. If the current THD is greater than the considered threshold in the *M* consecutive sample data windows, it can be concluded that increase of current THD is permanent. Increase of current THD is permanent for nonlinear loads switching and HIFs, but it is not permanent for linear loads switching and capacitors switching.

Current THD for linear load switching, capacitor switching, nonlinear load switching and HIF is shown in Figures 1, 2, 3, and 4 respectively.

Therefore if increase of current THD is permanent, it can be concluded that nonlinear load switching or HIF is occurred in network.

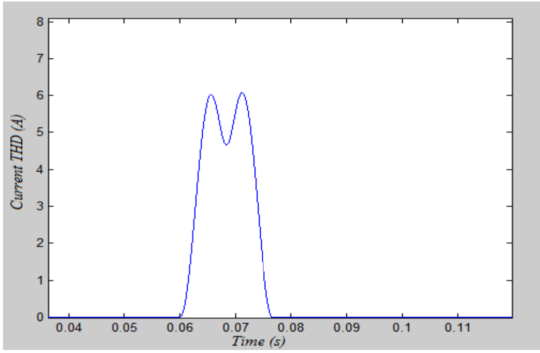

Figure 1. Current THD of linear load switching

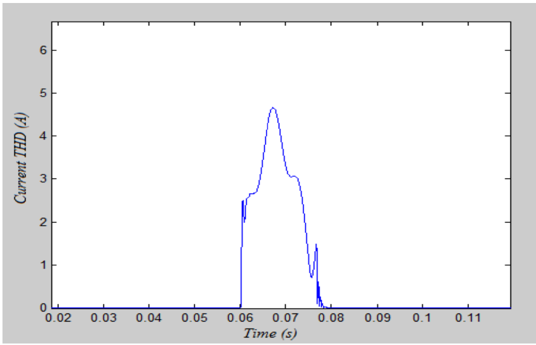

Figure 2. Current THD of capacitor switching

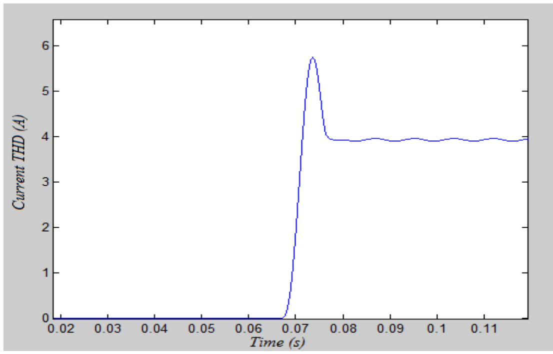

Figure 3. Current THD of nonlinear load switching

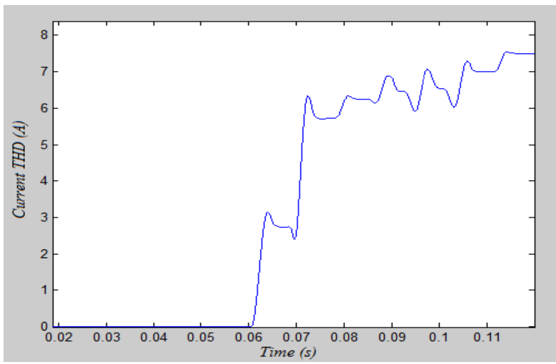

Figure 4. Current THD of HIF

In the many researches, randomness canonical is used for separation HIFs and nonlinear loads switching [11, 15], But this canonical is not good for HIFs detection due to random nonlinear loads switching in distribution feeders. In this paper, next two canonicals are used for separation HIFs and nonlinear loads switching simultaneously.

2.3. Third Harmonic of THD

In all HIFs, always current third harmonic is formed more than of half of current THD toward other harmonics [26, 35, 36], but usually that is not for nonlinear load switching. These properties are shown in Figures 5 and 6.

In this paper, these properties are used for separation HIFs and nonlinear loads switching and therefore HIFs are detected. According to relation (6), if α (ratio of third harmonic to THD) is greater than 50% HIF can be occurred; otherwise nonlinear load switching is occurred.

$$\alpha = \frac{h_3}{THD} . 100 \qquad (6)$$

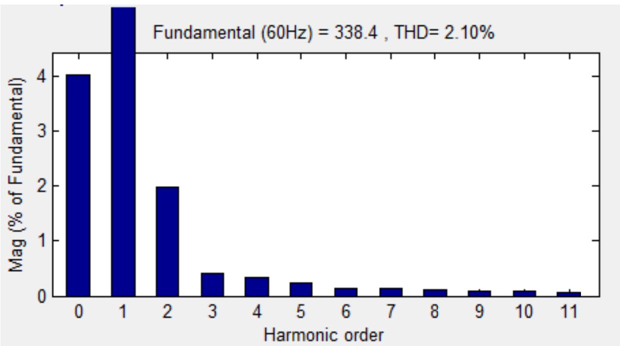

Figure 5. Harmonic spectrum of nonlinear load switching

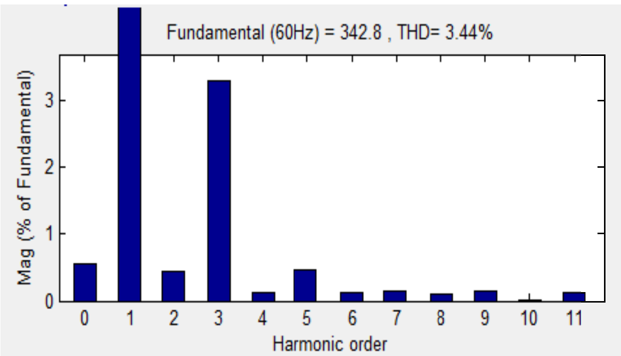

Figure 6. Harmonic spectrum of HIF

2.4. Time Variations

Always HIF current is about 60 per cent of its final value in beginning of fault occurrence and gradually over 3 to 4 cycles reaches its final value [37]. This property is common between all HIFs and obtained from tests in different conditions. Always current variations toward time are increased in the first few cycles after the occurrence of HIFs, but usually these variations are zero or variable (Increase and decrease) for nonlinear loads switching. These properties are shown in Figures 7, 8 and 9.

In this paper, these properties are used for separation HIFs and nonlinear loads switching. So if according to relation (7), β>0 or in other words $\beta$is strictly increasing in the first few cycles after the occurrence of disturbance, HIF can be occurred in network.

$$\beta = \frac{dIrms}{dt} \qquad (7)$$

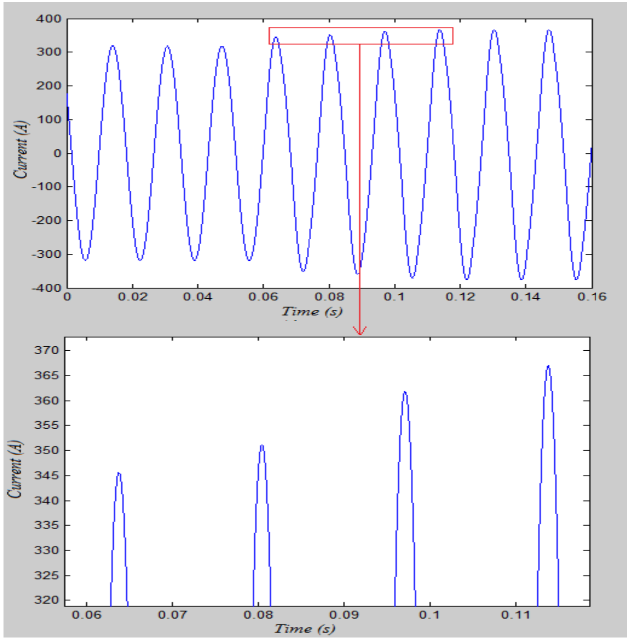

Figure 7. Current variations at relaying point for HIF

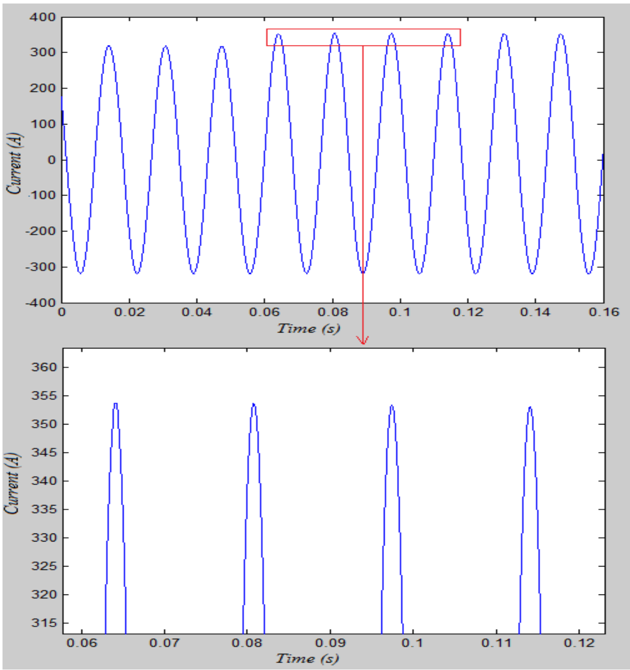

Figure 8. Current variations at relaying point for constant nonlinear load switching

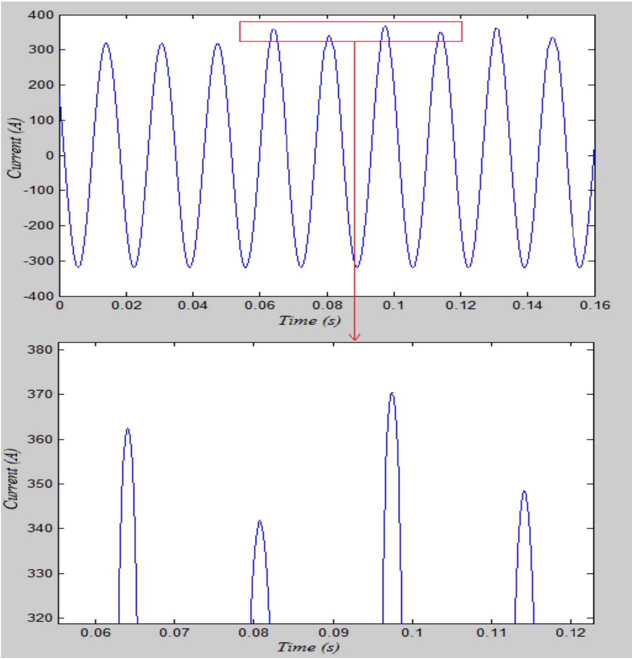

Figure 9. Current variations at relaying point for random nonlinear load switching

Reason of simultaneous use of canonicals 3 and 4 is increasing reliability of proposed method. If one of canonicals 3 or 4 for the phenomenon except the mentioned phenomena is similar to HIFs, HIFs can be detected by other canonical.

3. Proposed Detection Algorithm Implementaton

This algorithm is to discriminate between HIFs and other same phenomena such as linear and nonlinear loads switching and capacitors switching. Figure 10 shows the HIF detection procedure of the proposed method.

In this algorithm, after sampling of current waveform, I_{rms} is calculated. In the next stage using the FFT, the current harmonics is extracted. Using the extracted harmonics, the current THD is calculated. In the next stage, if the current THD is greater than the considered threshold, the algorithm will go to next stage and otherwise algorithm returns to the beginning of the algorithm. In next stage, $\alpha$is calculated, if α is greater than the %50, the algorithm will go to next stage and otherwise algorithm returns to the beginning of the algorithm. In the next stage, I_{rms} saved in the memory. Then algorithm checks stages listed for other M consecutive sample data windows and if the terms are realized, the algorithm will go to next stage. In the next stage, β is calculated for first four cycles which saved in the memory and if β is greater than zero, HIF is detected. Otherwise, algorithm returns to the beginning of the algorithm. "i" is a counter that signifies number of consecutive sample data windows.

This algorithm is able to HIFs detection only in networks without harmonic variations. But harmonics of network will vary with the entry and exit of nonlinear loads in network and the proposed algorithm will not able to HIFs detection. For solving this problem, the proposed algorithm is changed to Figure 11. As can be seen, instead of using the THD_i and h_{3i} have been used their variations ($\Delta THD_i=|THD_i-THD_{ref}|$, $\Delta h_{3i}=|h_{3i}-h_{3ref}|$). THD_{ref} and h_{3ref} will be updated with entry and exit any non-linear load in network. HIFs will be detected using the modified algorithm in all conditions.

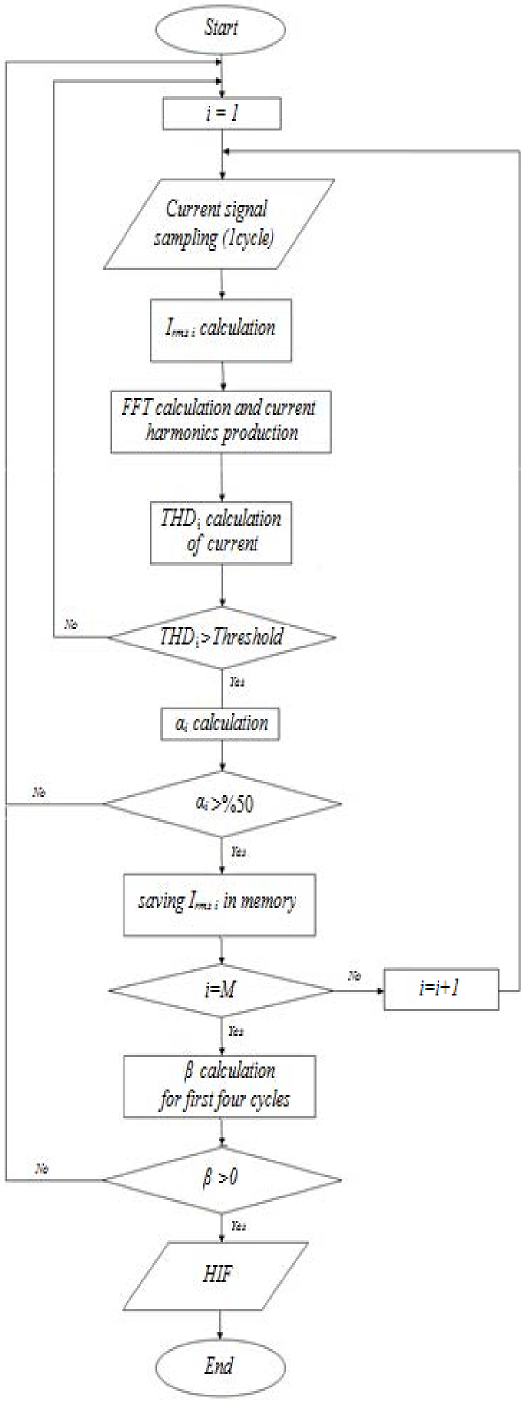

Figure 10.HIF detection procedure

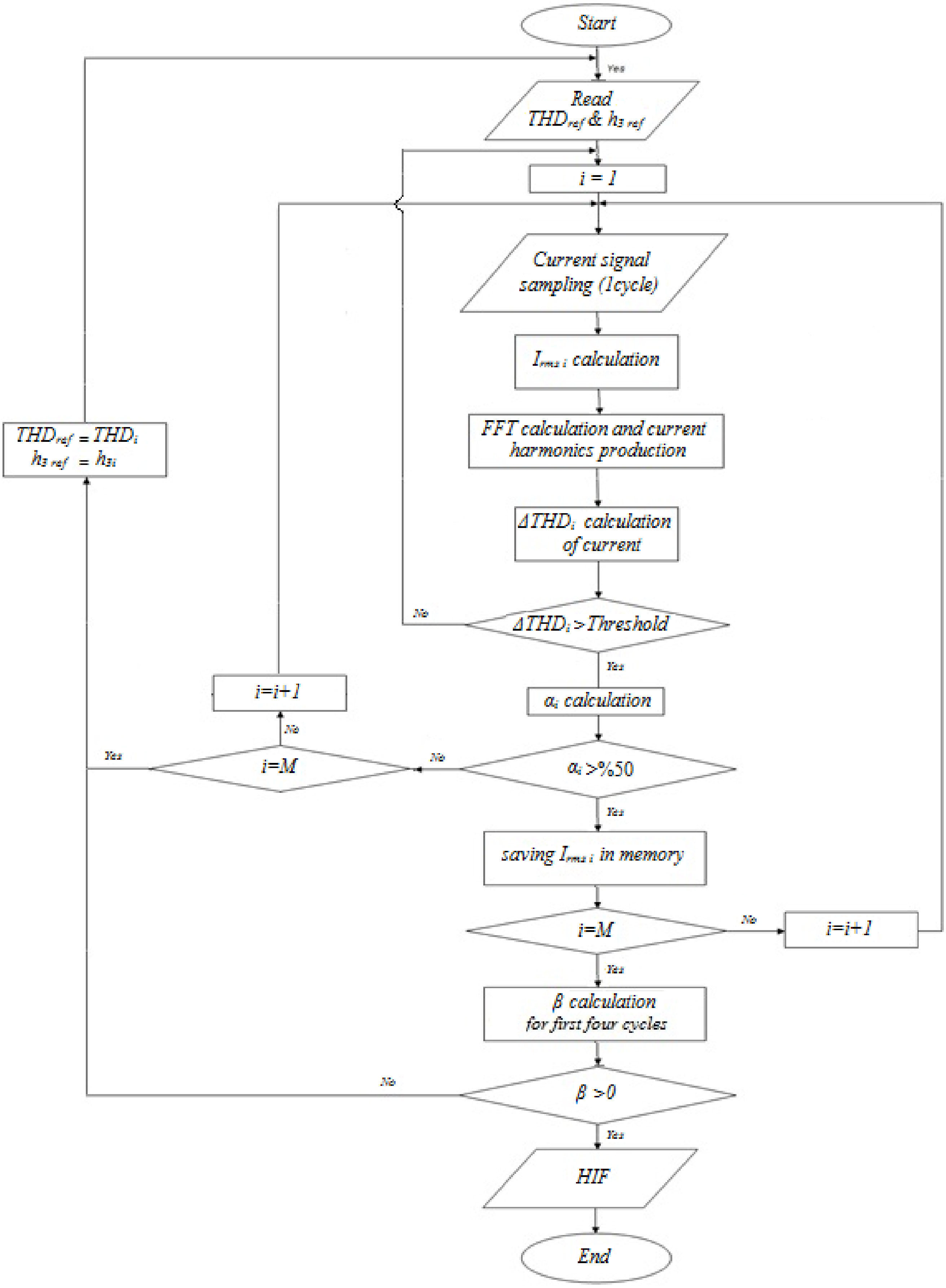

Figure 11. HIF detection generalized procedure

4. Modeling

4.1. HIF Model

Model of HIF makes up an important part of fault simulation. Emanuel model of HIF used in this paper is shown in the Figure 12. The model includes two DC sources, V_p and V_n, which represent the inception arc voltage between trees or soil and the distribution line. The two resistances $R_p$and R_n, represent the fault resistance: unequal values allows for asymmetric fault currents to be simulated. When the phase voltage is greater than the positive DC voltage V_p, the fault current flows toward the ground. The fault current reverses when the line voltage is less than the negative DC voltage V_n. For values of the phase voltage between V_p and V_n no fault current flows [10].

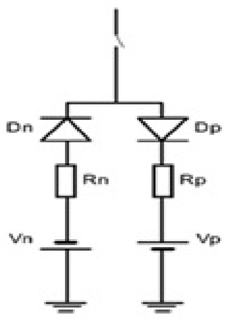

Figure 12. Emanuel model of HIF

According to Figure 13, when a HIF occurs, several arc with different intensities and simultaneously be created.

Figure 13. Arcs generated by HIF

In this paper, for consideration of this property in HIF model and better simulation, Emanuel model with multi-arc is used, that is shown in Figure 14. A typical current waveform under HIF phenomenon is shown in Figure 15.

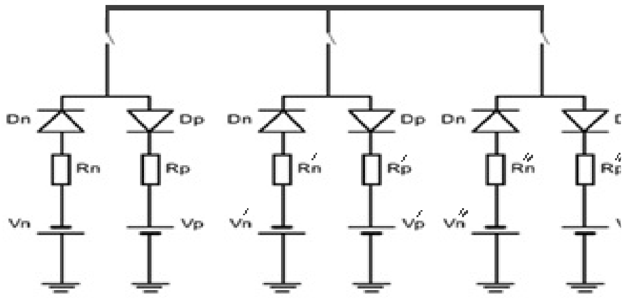

Figure 14. Emanuel model of HIF with three arcs

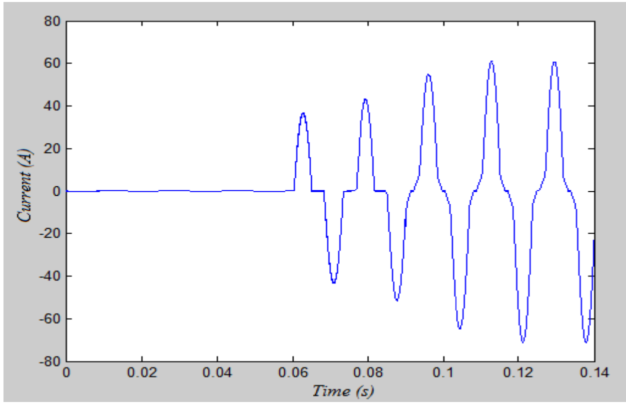

Figure 15. Current waveform of HIF

4.3. Nonlinear Load Model

Nonlinear loads are used in this paper.

1. One phase rectifier
2. Three phase diode pole

Loads are used in constant and random modes.

4.4. Distribution Network Model

The power system studied is in voltage level 20 kV which shown in Figure 16. Using of MATLAB power system toolbox, the test network is simulated. Circuit transmission lines parameters and loads characteristics of distribution network are shown in Tables 1 and 2, respectively.

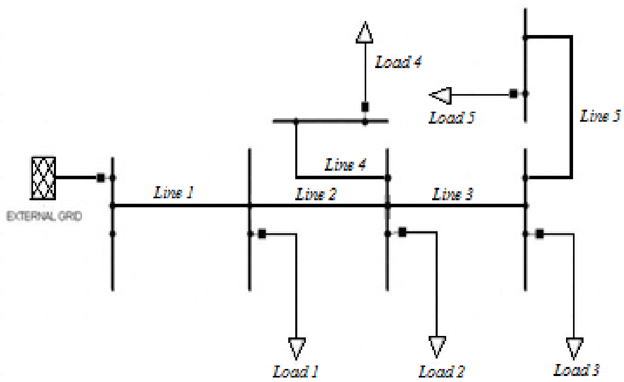

Figure 16. One-line diagram of distribution network

Table 1. Circuit Line Parameters

Positive sequence resistance R_1, Ω/km	0.01273
Zero sequence resistance R_0, Ω/km	0.3864
Positive sequence inductance L_1, mH/km	0.9337
Zero sequence inductance L_0, mH/km	4.1264
Positive sequence capacitance C_1, µF/km	0.0120
Zero sequence capacitance C_0, µF /km	0.0075

Table 2. Loads Characteristics

Load number	S (MVA)	Cos (phi)
1	1.75	0.85
2	1.4	0.85
3	2	0.9
4	0.87	0.86
5	0.375	0.8

5. Results

100 cases of HIF, 80 cases of nonlinear load switching, 80 cases of linear load switching, and 80 cases of capacitor switching on the distribution network are tested. Algorithm has been tested for M = 6 on the mentioned phenomena, which HIFs are well separated from other same phenomena and are detected. Some of the results are shown in the Table. 3. These are shown that increase of current THD is permanent and always current THD is greater than considered threshold for nonlinear loads switching and HIFs, but that is not for linear loads switching and capacitors switching. α and β are used for distinction between HIFs and nonlinear loads switching. α value is greater than 50% for HIFs and is smaller than 50% for nonlinear loads switching. β value is greater than zero for HIFs, but its value is zero or variable(positive and negative) for nonlinear loads switching.

6. Conclusion

The proposed method provides a new method for HIFs detection using FFT. The current harmonics are extracted by using FFT and calculated current THD. Then HIFs are detected by using four canonicals of current waveform: 1. THD extraction, 2. Stability of THD, 3. Third harmonic of THD, 4. Time variations. The proposed method has been tested under many variations of networks operating conditions including capacitors switching, linear and nonlinear loads switching which are similar to HIFs. The results obtained from the proposed method showed that HIFs can be detected and easily discriminated from other same phenomena.

Table 3. Results of Proposed Algorithm for N = 1, M = 6, Threshold = 0.05

Phenomenon		*i* = 1	*i* = 2	*i* = 3	*i* = 4	*i* = 5	*i* = 6
Linear load switching	*ΔTHD (%)*	2.4	0.02	0.01	0.01	0.01	0
Capacitor switching	*ΔTHD(%)*	3.44	0.24	0.09	0.06	0.04	0.02
Constant nonlinear load Switching	*ΔTHD(%)* α(%) I_{rms}(Relaying point) *(A)*	3.52 16.47 351.2	3.38 14.49 351.2	3.37 14.83 351.2	3.37 15.13 351.2	3.37 15.12 351.2	3.37 15.13 351.2
Random nonlinear load Switching	*ΔTHD(%)* *α(%)* I_{rms}(Relaying point) *(A)*	3.26 11.35 339.46	3.32 10.8 351.35	3.19 11.69 343.81	3.46 12.35 363.37	3.24 11.26 348.51	3.01 11.14 331.14
HIF 1	*ΔTHD(%)* *α(%)* I_{rms}(Relaying point) *(A)*	3.38 97.34 344.37	3.76 97.34 348.19	3.94 97.46 355.97	4.44 97.75 359.5	4.65 97.6 361.4	4.51 97.43 359.9
HIF 2	*ΔTHD(%)* *α(%)* I_{rms}(Relaying point) *(A)*	4.16 89.4 361.3	4.31 90.63 368.8	4.56 90.71 374.53	4.96 92.2 382.16	4.85 91.9 381.85	4.81 92.25 379.66
HIF 3	*ΔTHD (%)* *α(%)* I_{rms}(Relaying point) *(A)*	6.14 94.6 370.21	6.69 94.81 381.62	6.87 94.78 393.57	7.08 95.15 408.46	7.12 94.35 410.47	7.45 96.68 414.53

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